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A Detailed Phosphorus Characterization of Seventy-Eight Soils

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ABSTRACT

Sharpley, A.N., C.A. Jones, Carl Gray, and others. 1985. A Detailed Phosphorus Characterization of Seventy-Eight Soils. U.S. Department of Agriculture, Agricultural Research Service ARS-31, 32 pp.

This publication documents P analyses carried out on 78 soil samples. The samples, which represented seven major soil orders from all regions of the United States, were obtained from the Soil Conservation Service's National Soil Survey Laboratory. Relationships between the various P forms, soil P test values, and soil properties as they relate to the effects of pedogenesis on and modeling of soil P chemistry are summarized. Topics discussed in the publication are prediction of labile, organic, and sorbed P; relationship among soil P test values; pathways of soil P transformation; and relationships between P and soil test P.

KEYWORDS: Soil and plants phosphorus (P) model, pedogenesis, soil P, soils

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A DETAILED PHOSPHORUS CHARACTERIZATION OF SEVENTY-EIGHT SOILS[1]

A. N. Sharpley, C. A. Jones, Carl Gray, C. V. Cole, H. Tiessen, and C. S. Holzhey[2]

INTRODUCTION

A soil and plant phosphorus (P) model was developed for incorporation in the Erosion-Productivity Impact Calculator (EPIC) (Williams et al. 1983, 1984), which simulates erosion and its effects on the long-term productivity of soils (Jones et al. 1984). The model is designed to use soil chemical, physical, and taxonomic data available in U.S. Soil Conservation Service (SCS)/State Agricultural Experiment Station Soil Survey Investigative Reports and SCS pedon descriptions. Soil P data are not normally included in these reports and descriptions and must be obtained elsewhere. For this reason, data required to initialize the P model have been minimized.

Three P-related parameters must be measured or estimated to initialize the model. They are initial labile P (represented by anion-exchange resin P), initial organic P, and an index of fertilizer P availability. None of these parameters are readily obtainable from soil testing services and, therefore, must be estimated from more readily available data.

The representation of available P in soil P models is complicated by a variance from state to state in methodology used to measure soil test P (Nelson et al. 1953b; Jones 1973). Consequently, relationships between soil P tests are needed so that

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a consistent set of input data can be generated for model application. Since soil weathering influences the forms and stability of soil P (Walker and Syers 1976), it is expected that relationships between soil P tests will vary and different P fractions will be extracted, depending on the degree of soil weathering. Little information is available, however, on the relationships between tests for P fertility and soil P fractions of differing stability as a function of soil weathering. For this reason, a coordinated study was initiated to examine the effects of soil weathering and soil properties on labile soil P, on P extracted by routine soil tests, on fertilizer P adsorption, and on soil organic P.

Seventy-eight surface soil samples (A1 and Ap horizons), representing seven major soil orders, from all regions of the United States, were obtained from the Soil Conservation Service, National Soil Survey Laboratory, Lincoln, Nebraska. Soils were chosen on the basis of their agricultural importance, availability of soil samples, and availability of adequate laboratory data for the samples. This report details the physical and chemical properties of these soils as determined by the SCS National Soil Survey Laboratory, Lincoln, Nebraska; Saskatchewan Institute of Pedology; Texas Agricultural Extension Service Soil Testing Laboratory; and USDA-ARS at Ft. Collins, Colorado, Durant, Oklahoma, and Temple, Texas. In addition, relationships obtained between various P forms, soil P test values and soil properties, as they relate to the effects of pedogenesis on and modeling of soil P chemistry, are summarized. Preliminary results of this study have been reported (Sharpley et al. 1984a, 1984b).

The objective of this paper is to report the results of analyses made in this study and to encourage other researchers to explore the relationships among the soil properties measured.

MATERIALS AND METHODS

Particle-size analysis, pH, cation exchange capacity, base saturation, electrical conductivity, organic carbon, total nitrogen, calcium carbonate, and extractable iron and aluminum were determined by the SCS, National Soil Survey Laboratory, Lincoln, Nebraska, according to standard procedures outlined on each soil survey report and detailed by SCS (1972; 1984).

Soil test P was measured by resin, Bray I, Mehlich I (North Carolina or double acid), Olsen bicarbonate, Texas A&M, and water procedures on air-dried, sieved (2 mm) soil. Anion exchange resin P was determined by adding 5 cm^3 IRA-400 anion exchange resin (bicarbonate form) to 4 g soil in 40 ml

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water. The sample was shaken on an oscillating shaker at 180 oscillations min^{-1} for 16 h. A 60-mesh screen was used to separate soil from resin. Phosphorus was removed from the resin with 100 ml 1.5 M NaCl for 24 h with occasional stirring. Bray I P was determined by the method of Bray and Kurtz (1945), where 2 g soil was shaken in 20 ml of 0.03 M NH_4F and 0.025 M HCl for five min. Mehlich I P was extracted by shaking 5 g soil with 20 ml 0.05 M HCl and 0.0125 M H_2SO_4 for 5 min (Nelson et al. 1953a). Olsen bicarbonate P was determined by shaking 1 g soil with 20 ml 0.5 M $NaHCO_3$ (pH 8.5) for 5 min (Olsen et al. 1954). Texas A&M P was extracted by shaking 1 g of soil in 25 ml of 1.43 M NH_4OAc (pH 4.2) and 0.025 M EDTA for 30 min. Water P was determined by shaking 5 g soil with 50 ml of distilled water for 5 min (Olsen and Sommers, 1982).

An index of soil P sorption was estimated by adding 0, 0.06, 0.12, 0.24, and 0.48 mg P (as $KHPO_4$) to 4 g subsamples of soil in small plastic vials. Soil was brought to field capacity with distilled water and allowed to dry in the laboratory. The soil was rewet and allowed to dry twice more during a 6-month period before extraction with anion exchange resin. The relationship between resin P and P added (as mg P $kg\ soil^{-1}$) was determined by linear regression analysis, and the sorption index [g P extracted $(g\ P\ added)^{-1}$] is the slope of that relationship for each soil.

Soil was ground to 100 mesh and extracted sequentially with anion exchange resin (bicarbonate form), 0.5 M $NaHCO_3$ (pH 8.5), 0.1 M NaOH, sonification followed by 0.1 M NaOH, 1.0 M HCl and, conc. H_2SO_4 and H_2O_2 (Hedley et al. 1982; Tiessen et al. 1984). The inorganic P contents of each extract were determined and are subsequently referred to as resin Pi, bicarbonate Pi, hydroxide Pi, sonicate Pi, acid Pi, and residual P, respectively. The total P content of each soil was determined independently by digestion with conc. H_2SO_4 and H_2O_2. In addition, the organic P contents of the bicarbonate, hydroxide, and sonicate extracts were calculated as the difference between inorganic P and total P contents of each extract and are subsequently referred to as bicarbonate Po, hydroxide Po, and sonicate Po, respectively. In all cases, P concentration was measured on neutralized extracts by the method of Murphy and Riley (1962).

The sequential extraction procedure removes inorganic and organic P of increasing chemical stability in terms of soil P fertility. Hedley et al. (1982) proposed that resin and bicarbonate (extractable) Pi are the most biologically available Pi forms, while hydroxide Pi is associated with amorphous and some crystalline Al and Fe phosphates. Sonicate Pi is

likely located within soil aggregates which are broken down with sonification. Acid Pi is mainly relatively stable Ca-bound P. Bicarbonate Po is easily mineralized and contributes to plant available P. The hydroxide and sonicate Po constitute chemically and physically protected organic forms that are involved in long-term soil P transformations.

RESULTS

Preliminary results reported in Sharpley et al. (1984b) showed that estimation of labile P from soil test P was improved when the 78 soils were divided into groups based on the presence of $CaCO_3$; highly weathered soils--Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols, and Dystric suborders of Inceptisols; and slightly weathered soils--all other soils (mostly Mollisols, Alfisols, and Vertisols). The soil series name, pedon number, classification, and current and previous land use for the calcareous and slightly and highly weathered soils are given in Tables 1 to 3. Several soil samples (for example, Pullman, pedon number S80TX-303-1 and Shelby, pedon number S80NE-109-1) are not normally calcareous but were found to contain trace amounts of $CaCO_3$ probably due to liming or mixing of subsurface carbonates. They were placed in the slightly weathered group. In addition, some of the slightly weathered soils are more highly weathered than those in the highly weathered group and vice versa. The above soil grouping does not, therefore, represent an exact sequence of degree of weathering, it is used, however, as the soils in each group behaved similarly, in terms of relationships between P forms.

Physical (particle-sized analysis) and chemical (pH, CEC, base saturation, and electrical conductivity) properties of the three groups of soil as determined by the SCS are presented in tables 4 to 6. Soil chemical characterization data (organic C, total N, $CaCO_3$, Fe, and Al), also determined by SCS, are given in tables 7 to 9.

Soil test P represented by resin, Bray I, Mehlich I, Olsen, Texas A&M, and water procedures and P sorption index as determined by the Texas Agricultural Extension Service for each soil are presented in tables 10, 11, and 12 for the calcareous, slightly, and highly weathered soils, respectively.

The fractionation of inorganic and organic P as carried out by the Saskatchewan Institute of Pedology is presented in tables 13, 14, and 15 for the calcareous, slightly, and highly weathered soils, respectively. The following discussion summarizes some of the relationships investigated among soil test P, P fractions, and soil chemical and physical properties.

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DISCUSSION

Prediction of Labile, Organic, and Sorbed P

Regression analysis, conducted with the SAS STEPWISE and REG procedures (Barr et al. 1979), was used to obtain equations to predict labile P, organic P, and a P sorption index from soil chemical and physical properties (Sharpley et al. 1984b). Labile P was linearly related to the amount of P extracted by the Bray I, Olsen, Mehlich I, and Texas A&M techniques (table 16). The organic P content (mg . kg $soil^{-1}$) of the soils in this study was linearly related (R^2 = 0.64) to total N (mg.kg $soil^{-1}$) in all groups of soils according to the following regression equation,

Organic P = 44.4 + 0.113 Total N

The soil P model (Jones et al. 1984) uses a laboratory estimate of the fraction of added fertilizer P which remains in the labile (anion exchange resin-extractable) or extractable form. This fraction represents an index of both P sorption and fertilizer P availability, and was related to soil physical and chemical properties (table 17). Fertilizer P availability increased with a decrease in $CaCO_3$ and clay content for the calcareous and highly weathered soils, respectively. For the slightly weathered soils an increase in labile P, base saturation, and pH was associated with an increase in fertilizer P availability.

Although equations used to estimate labile, organic, and fertilizer P availability are empirical, independent variables chosen in the stepwise regression were consistent with P mineralization and sorption relationships previously reported. These relationships were tested using independent data sets. They can be used to generate input for the soil P model from soil test P and data available in SCS/Soil Survey Reports.

Relationship Among Soil P Test Values

The soil P test methods, Bray I, Mehlich I, and Olsen were linearly related (table 18). Coefficients of determination (R^2) ranged from 0.00 to 0.90. Lower coefficients were obtained between Mehlich I and Olsen tests, as these extractants were developed for differing soil types. Texas A&M P was not related to soil test P as determined by the other methods for the calcareous soils (table 18). The correlation increased, however, for slightly and highly weathered soils. The lack of any significant relationship between Texas A&M P and the other tests may result from the dissolution of Ca - P compounds by the more acidic Texas A&M extractant (pH 4.2). Using independent data sets, the regression equations provided accurate estimates of soil test P by one method from another (Sharpley et al. 1984a).

Pathways of Soil P Transformations

The distribution of P across the different extractions (resin, bicarbonate, hydroxide, sonification-2nd hydroxide, acid, and acid-peroxide digest with separate organic and inorganic P determinations) and their relationships to other soil chemical properties were used to evaluate the effects of differing soil development on phosphorus composition (Tiessen et al. 1984).

Correlation and regression analyses of P distribution and chemical analyses confirmed the partial dependence of organic matter accumulation on available forms of P. Weathering indicators such as base saturation were related to the formation of secondary P forms. The relative proportions of available and stable (fixed), as well as organic and inorganic P forms, were dependent upon soil chemical properties and related to soil taxonomy.

Path analysis of relationships between labile and stable P forms showed that in Mollisols much of the labile resin-extractable P was derived from inorganic bicarbonate and hydroxide extractable P forms. In Ultisols, 80% of the variability in labile P was accounted for by organic P forms, suggesting that mineralization of organic P may be a major determinant of P fertility in these soils.

Analysis of the phosphorus data based on accepted concepts of the soil P cycle clearly shows that available P, and, therefore, the agronomically important P, in highly developed soils is closely related to the organic P fractions. This may explain the many difficulties encountered in the testing of P fertility in tropical and subtropical soils and indicates that the study of labile forms of Po might contribute to advances in soil test procedures.

Relationships Between P Fractions and Soil Test P

Relationships between inorganic and organic P fractions and soil test P were investigated to determine the relative contribution of resin-extractable labile and more stable inorganic and organic P fractions to soil test P. Labile P was correlated with Bray I and Olsen P in calcareous (R^2 of 0.83 and 0.75), slightly weathered (R^2 of 0.75 and 0.74), and highly weathered soils (R^2 of 0.79 and 0.63). Mehlich I P explained only 50 and 39% of the variation in labile P in calcareous and slightly weathered soils, but it explained 87% of the variation in highly weathered soils. Only in highly weathered soils did Texas A&M P explain more than 50% of the variation in labile P (R^2 of 0.76). In the highly weathered soils, consideration of organic P turnover may improve the fertility prediction of soil P tests, due to the increased importance of organic P in soil-P cycling.

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CONCLUSIONS

The preceding discussion summarizes some of the relationships between soil P characteristics that we have investigated, to give an idea of how we have used the data presented in tables 1 to 15. We hope that documentation of these data will facilitate its use by other researchers. If there are any questions or comments concerning methodology used and results reported, please contact the authors.

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Table 1. Classification, SCS pedon number, and current and previous land use of the calcareous soils.

Soil Series	Pedon Number	Classification	Land Use+	
			Prev.	Cur.
AVONDALE	S80AZ-21-1	Fine-loamy, mixed (calcareous), hyperthermic, Typic Torrifluvent	.	1
BONE	S77WY-5-4	Fine, montmorillonitic (calcareous), mesic, Ustic Torriorthent	.	5
BOSQUE	S81TX-27-2	Fine-loamy, mixed, thermic, Cumulic Haplustoll	.	2
CATALPA	S81MS-81-3	Fine, montmorillonitic, thermic, Fluvaquentic Hapludoll	3	6
COLY	S80NE-175-62	Fine-silty, mixed (calcareous), mesic, Typic Ustorthent	.	5
CROFTON	S79NE-119-2	Fine-silty, mixed (calcareous), mesic, Typic Ustorthent	.	5
FRUITLAND	S81NM-45-2	Coarse-loamy, mixed, mesic Typic Camborthid	.	8
HOCHHEIM	S68WI-8-1	Fine-loamy, mixed, mesic, Typic Argiudoll	7	9
HOUSTON BLACK	S77TX-27-2	Fine, montmorillonitic, thermic, Udic Pellustert	.	5
JOPLIN	S62MT-51-2	Fine-loamy, mixed, Aridic Agriboroll	.	8
KENT	S70MI-16-1	Fine, illitic, Typic Eutroboralf	.	8
KIDMAN	S81UT-11-1	Coarse-loamy, mixed, mesic, Calcic Haploxeroll	.	1
LEEPER	S81MS-81-2	Fine, montmorillonitic, nonacid, thermic, Vertic Haplaquept	.	3
MILLVILLE	S81UT-5-1	Coarse-silty, carbonatic, mesic, Typic Haploxeroll	.	1
SANPETE	S75UT-41-7	Loamy-skeletal, carbonatic, mesic, Xerollic Calciorthid	.	5
VENUS	S81TX-27-1	Fine-loamy, mixed, thermic, Typic Calciustoll	.	2
WAYDEN	S77ND-1-4	Clayey, montmorillonitic (calcareous), frigid, shallow, Typic Ustorthent	.	1
WITT	S80CO-83-1	Fine-silty, mixed, mesic, Ustollic Haplargid	.	6

+ Soil use code: 1 = small grain, 2 = row crops, 3 = annual legumes, 4 = perennial legumes, 5 = natural rangeland, 6 = improved pasture or 7 = woodland or forest, 8 = fallow, 9 = mixed rotation or "cultivated."

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Table 2. Classification, SCS pedon number, and current and previous land use of the slightly weathered soils.

Soil Series	Pedon Number	Classification	Land Use+	
			Prev.	Cur.
ABSTED	S77WY-5-5	Fine, montmorillonitic, mesic, Haplustollic Natrargid	.	5
ACUFF	S81TX-69-2	Fine-loamy, mixed, thermic, Aridic Paleustoll	.	6
ALO	S71CA-30-8	Fine, montmorillonitic, thermic, Typic Chromoxerert	.	5
AMARILLO	S81TX-227-3	Fine-loamy, mixed, thermic, Aridic Paleustalf	.	9
AMSTERDAM	S80MT-31-1	Fine-silty, mixed, Typic Haploboroll	.	1
BEARPAW-LIKE	S62MT-3-2	Fine, montmorillonitic, Typic Argiboroll	.	5
BEARPAW-LIKE	S80MT-15-1	Fine, montmorillonitic, Typic Argiboroll	.	4
CALLOWAY	S78LA-67-4	Fine-silty, mixed, thermic, Glossaquic Fragiudalf	.	7
CHILCOTT	S79ID-39-1	Fine, montmorillonitic, mesic, Abruptic Xerollic Durargid	.	5
CRETE	S80NE-59-18	Fine, montmorillonitic, mesic, Pachic Argiustoll	.	1
FAYETTE	S61IL-50-1	Fine-silty, mixed, mesic, Typic Hapludalf	7	6
GRUNDY	S73MO-32-1	Fine, montmorillonitic, mesic, Aquic Argiudoll	.	9
HAGERSTOWN	S75PA-27-1	Fine, mixed, mesic, Typic Hapludalf	7	6
HARNEY	S68KS-26-14	Fine, montmorillonitic, mesic, Typic Argiustoll	.	5
HASTINGS	S65NE-91-1	Fine, montmorillonitic, mesic, Udic Argiustoll	.	5
HAYDEN	S74MN-163-6	Fine-loamy, mixed, mesic, Typic Hapludalf	7	4
HOSMER	S62IL-44-2	Fine-silty, mixed, mesic, Typic Fragiudalf	.	6
JULESBURG	S63CO-58-2	Coarse-loamy- mixed, mesic, Aridic Argiustoll	.	9
LORING	S78LA-67-3	Fine-silty, mixed, thermic, Typic Fragiudalf	.	7
MACKSBURG	S61IA-61-1	Fine, montmorillonitic, mesic, Aquic Argiudoll	.	6

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Table 2 continued.

Soil Series	Pedon Number	Classification	Land Use+ Prev.	Land Use+ Cur.
MARSHALL	S63IA-83-1	Fine-silty, mixed, mesic, Typic Hapludoll	.	4
MAURY	S80KY-67-1	Fine, mixed, mesic, Typic Paleudalf	.	2
MODJESKA	S71CA-30-2	Loamy-skeletal, mixed, thermic, Typic Xerochrept	.	1
MUSCATINE	S60IA-38-1	Fine-silty, mixed, mesic, Aquic Hapludoll	.	5
MUSCATINE	S76IA-103-1	Fine-silty, mixed, mesic, Aquic Hapludoll	.	6
NORGE	S80OK-17-3	Fine, mixed, thermic, Udertic Paleustalf	.	5
PALOUSE	S77WA-75-1	Fine-silty, mixed, mesic, Pachic Ultic Haploxeroll	5	9
PAYNE	S81TX-27-3	Fine, montmorillonitic, thermic, Udic Paleustalf	.	4
PROMISE	S78SD-11-41	Very-fine, montmorillonitic, mesic, Udic Chromustert	5	2
PULLMAN	S80TX-375-1	Fine, mixed, thermic, Torrertic Paleustoll	9	8
PULLMAN	S80TX-303-1	Fine, mixed, thermic, Torrertic Paleustoll	2	3
RICHFIELD	S63CO-58-9	Fine, montmorillonitic, mesic, Aridic Argiustoll	.	9
RUSSIAN	S78CA-45-110	Coarse-loamy, mixed, thermic, Cumulic Haploxeroll	.	.
SHELBY	S80NE-109-1	Fine-loamy, mixed, mesic, Typic Argiudoll	.	6
TAMA	S76IA-103-2	Fine-silty, mixed, mesic, Typic Argiudoll	.	2
ULY	S79NE-175-36	Fine-silty, mixed, mesic, Typic Haplustoll	.	5
WYMORE	S73NE-55-2	Fine, montmorillonitic, mesic, Aquic Argiudoll	.	6
ZANESVILLE	S80KY-33-2	Fine-silty, mixed, mesic, Typic Fragiudalf	.	2

+ Soil use code: 1 = small grain, 2 = row crops, 3 = annual legumes, 4 = perennial legumes, 5 = natural rangeland, 6 = improved pasture or 7 = woodland or forest, 8 = fallow, 9 = mixed rotation or "cultivated."

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Table 3. Classification, SCS pedon number, and current and previous land use of the highly weathered soils.

Soil Series	Pedon Number	Classification	Land Use+	
			Prev.	Cur.
AGAWAM	S78NH-5-23	Coarse-loamy over sandy, mixed, mesic, Typic Dystrochrept	.	6
AGAWAM	S7OVT-9-1	Coarse-loamy over sandy or sandy skeletal, mixed, frigid, Typic Dystrochrept	.	9
APPLING	S78VA-111-1	Clayey, kaolinitic, thermic, Typic Hapludult	7	.
BERTIE	S81NC-15-1	Fine-loamy, mixed, thermic Aquic Hapludult	.	2
CARIBOU	S75ME-3-1	Fine-loamy, mixed, frigid, Typic Haplorthod	7	8
CATALINA	S59PR-10-7	Clayey, oxidic, isohyperthermic, Tropeptic Haplorthox	.	6
DAVIDSON	S8OGA-237-1	Clayey, kaolinitic, thermic, Rhodic Paleudult	.	6
DOTHAN	S8OAL-37-1	Fine-loamy, siliceous, thermic, Plinthic Paleudult	7	3
HOLLAND	S77CA-19-13	Fine-loamy, mixed, mesic, Ultic Haploxeralf	.	7
LAKE	S81FL-1-1	Hyperthermic, coated, Typic Quartzipsamment	.	2
LAKELAND	S81FL-121-1	Thermic, coated, Typic Quartzipsamment	.	2
MADISON	S78VA-145-8	Clayey, kaolinitic, thermic, Typic Hapludult	.	6
MARDIN	S75NY-109-1	Coarse-loamy, mixed, mesic, Typic Fragiochrept	7	2
MILLHOPPER	S81FL-1-3	Loamy, siliceous, hyperthermic, Grossarenic Paleudult	.	1
NORFOLK	S8ONC-85-4	Fine-loamy, siliceous, thermic, Typic Paleudult	.	9
PAXTON	S75CT-13-1	Coarse-loamy, mixed, mesic, Typic Dystrochrept	.	6
RABUN	S78VA-3-1	Clayey, kaolinitic, mesic, Typic Rhodudult	.	6
RUSTON	S81LA-27-1	Fine-loamy, siliceous, thermic, Typic Paleudult	.	7
SASSAFRAS-LIKE	S79VA-1-1	Fine-loamy, mixed, thermic, Typic Hapludult	.	.
SOSA	S81PR-7-3	Clayey, oxidic, isohyperthermic, Plinthic Haplustult	.	6
STOCKBRIDGE	S81VT-21-3	Coarse-loamy, mixed, mesic, Dystric Eutrochrept	.	2

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Table 3 continued.

Soil Series	Pedon Number	Classification	Land Use+	
			Prev.	Cur.
TIFTON	S81GA-277-11	Fine-loamy, siliceous, thermic, Plinthic Paleudult	.	6

+ Soil use code: 1 = small grain, 2 = row crops, 3 = annual legumes, 4 = perennial legumes, 5 = natural rangeland, 6 = improved pasture or 7 = woodland or forest, 8 = fallow, 9 = mixed rotation or "cultivated."

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Table 4. Physical and chemical properties of the calcareous soils as determined by SCS.

Soil Series	Particle Size Analysis+			pH 1:1 H_2O	Cation Exchange Capacity	Base Sat.	EC
	Sand	Silt	Clay				
	%				$mmol(+)kg^{-1}$	%	$dS\ m^{-1}$
AVONDALE	37.2	42.3	20.5	8.4	148	100	.69
BONE	34.6	43.7	21.7	7.1	100	100	5.70
BOSQUE	8.5	61.9	29.6	8.3	235	100	.
CATALPA	25.2	44.4	30.4	7.4	277	100	.
COLY	21.6	51.6	26.8	7.4	238	100	.
CROFTON	14.5	62.3	23.2	8.0	226	100	.
FRUITLAND	71.2	16.9	11.9	8.2	100	100	.76
HOCHHEIM	27.5	55.4	17.1	7.4	152	100	.
HOUSTON BLACK	3.9	39.0	57.1	7.5	552	100	.
JOPLIN	51.8	25.8	22.4	7.7	156	100	.
KENT	66.9	22.2	10.9	7.1	108	100	.
KIDMAN	45.9	37.2	16.9	7.5	139	100	.43
LEEPER	9.1	55.2	35.7	7.6	254	100	.
MILLVILLE	29.6	57.2	13.2	8.3	111	100	.40
SANPETE	51.7	30.1	18.2	8.2	99	100	.56
VENUS	66.2	23.6	10.2	8.3	75	100	.
WAYDEN	5.6	46.6	45.8	7.7	375	100	.60
WITT	47.0	42.2	10.8	7.3	131	100	.93

+ Sand, silt, and clay represent material between 2 mm - 50 um, 50 um - 2 um, and < 2 um, respectively.

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Table 5. Physical and chemical properties of the slightly weathered soils as determined by SCS.

Soil Series	Particle Size Analysis+			pH 1:1 H_2O	Cation Exchange Capacity	Base Sat.	EC
	Sand	Silt	Clay				
	%				$mmol(+)kg^{-1}$	%	$dS\ m^{-1}$
ABSTED	58.5	35.4	6.1	6.5	53	100	.13
ACUFF	52.9	26.9	20.2	7.8	151	100	.77
ALO	13.3	35.9	50.8	6.4	417	95	.96
AMARILLO	83.1	8.0	8.9	8.3	55	100	.
AMSTERDAM	18.7	55.8	25.5	7.6	231	100	.55
BEARPAW-LIKE	48.7	29.2	22.1	6.6	164	97	.
BEARPAW-LIKE	18.1	41.2	40.7	7.7	221	94	.11
CALLOWAY	16.9	71.2	11.9	5.3	94	40	.
CHILCOTT	26.5	61.3	12.2	6.5	148	95	.72
CRETE	8.6	68.0	23.4	5.6	208	93	.
FAYETTE	3.6	81.5	14.9	5.7	119	76	.
GRUNDY	4.8	72.1	23.1	6.5	234	81	.
HAGERSTOWN	14.8	66.7	18.5	5.5	117	44	.
HARNEY	.	.	.	7.0	.	.	.
HASTINGS	9.5	67.4	23.1	5.9	182	94	.
HAYDEN	61.1	31.3	7.6	6.8	91	98	.
HOSMER	1.4	84.8	13.8	5.2	75	59	.
JULESBURG	86.9	6.2	6.9	6.7	60	97	.
LORING	19.5	69.9	10.6	5.5	98	66	.
MACKSBURG	2.4	65.0	32.6	6.3	258	100	.
MARSHALL	2.6	68.4	29.0	6.2	226	99	.
MAURY	6.3	70.7	22.5	6.55	126	94	.
MODJESKA	47.4	37.5	15.1	6.0	116	81	.
MUSCATINE	3.0	64.2	32.8	6.1	283	99	.
MUSCATINE	3.6	71.1	25.3	5.6	253	70	.
NORGE	32.7	45.8	21.5	6.1	139	91	.
PALOUSE	9.3	68.5	22.2	6.0	237	97	.
PAYNE	32.7	41.6	25.7	7.3	208	100	.
PROMISE	3.6	34.0	62.4	7.0	428	97	.24
PULLMAN	18.3	49.7	32.0	7.5	209	100	.
PULLMAN	39.4	30.7	29.9	8.0	223	100	.
RICHFIELD	43.8	39.1	17.1	6.2	129	95	.
RUSSIAN	43.4	42.3	14.3	5.6	163	90	.
SHELBY	40.7	33.9	25.4	7.1	192	100	.
TAMA	2.2	68.1	29.7	7.3	236	93	.
ULY	21.4	45.6	33.0	6.9	243	97	.
WYMORE	6.8	61.8	31.4	5.8	.	.	.
ZANESVILLE	8.0	75.5	16.5	5.8	94	81	.

+ Sand, silt, and clay represent material between 2 mm - 50 um, 50 um - 2 um, and < 2 um, respectively.

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Table 6. Physical and chemical properties of the highly weathered soils as determined by SCS.

Soil Series	Particle Size Analysis+			pH 1:1 H_2O	Cation Exchange Capacity	Base Sat.	EC
	Sand	Silt	Clay				
	%				$mmol(+)kg^{-1}$	%	$dS\ m^{-1}$
AGAWAM	40.8	55.9	3.3	6.2	90	74	.
AGAWAM	36.5	56.3	7.2	6.1	124	71	.
APPLING	62.4	25.6	12.0	4.4	46	11	.
BERTIE	85.0	12.2	2.8	5.6	17	65	.
CARIBOU	38.9	46.8	14.3	5.3	130	33	.
CATALINA	6.0	18.2	75.8	5.1	162	44	.
DAVIDSON	57.8	21.8	20.4	5.9	62	58	.
DOTHAN	82.1	9.0	8.9	6.8	30	100	.
HOLLAND	54.3	28.9	16.8	5.7	205	43	.
LAKE	96.3	1.3	2.4	5.6	13	69	.
LAKELAND	96.0	2.0	2.0	5.8	24	92	.
MADISON	55.5	30.9	13.6	5.4	54	56	.
MARDIN	24.5	57.9	17.6	5.1	115	47	.
MILLHOPPER	96.1	3.5	0.4	6.2	18	89	.
NORFOLK	75.7	21.9	2.4	4.9	25	32	.
PAXTON	60.0	29.0	11.0	5.6	171	39	.
RABUN	12.5	28.2	59.3	5.6	146	50	.
RUSTON	60.7	35.2	4.1	4.8	22	18	.
SASSAFRAS-LIKE	66.3	26.9	6.8	5.0	111	70	.
SOSA	81.8	6.3	11.9	5.7	52	83	.
STOCKBRIDGE	.	.	.	.	.	.	.
TIFTON	86.5	7.0	6.5	5.7	26	54	.

+ Sand, silt, and clay represent material between 2 mm - 50 um, 50 um - 2 um, and < 2 um, respectively.

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Table 7. Chemical characterization data for the calcareous soils as determined by SCS.

Soil Series	Organic C	Total N	Calcium Carbonate	Fe	Al
	---------- g kg^{-1} ----------				
AVONDALE	5	0.6	50	.	.
BONE	8	.	TR	.	.
BOSQUE	13	.	330	.	.
CATALPA	21	.	TR	.	.
COLY	18	1.6	TR	.	.
CROFTON	15	1.2	50	.	.
FRUITLAND	4	0.4	TR	.	.
HOCHHEIM	16	1.5	30	11	.
HOUSTON BLACK	32	2.6	210	.	.
JOPLIN	13	1.3	10	8	.
KENT	18	.	TR	.	.
KIDMAN	8	.	TR	.	.
LEEPER	16	.	TR	.	.
MILLVILLE	12	.	490	.	.
SANPETE	10	1.0	540	.	.
VENUS	4	.	30	.	.
WAYDEN	14	1.4	20	.	.
WITT	14	1.1	TR	7	1.0

BEST COPY AVAILABLE

Table 8. Chemical characterization data for the slightly weathered soils as determined by SCS.

Soil Series	Organic C	Total N	Calcium Carbonate	Fe	Al
	---------- g kg^{-1} ----------				
ABSTED	8	.	.	.	.
ACUFF	14	1.2	.	7	.
ALO	14	1	.	11	.
AMARILLO	2	.30	.	.	.
AMSTERDAM	9	.77	.	.	.
BEARPAW-LIKE	21	1.9	.	.	.
BEARPAW-LIKE	14	1.3	.	.	.
CALLOWAY	20	1.2	.	13	2.0
CHILCOTT	21	1.4	.	5	1.0
CRETE	23	1.9	.	.	.
FAYETTE	16	1.6	.	7	.
GRUNDY	21	.	.	11	.
HAGERSTOWN	14	.	.	27	.
HARNEY	.	.	.	.	.
HASTINGS	25	2	.	5	.
HAYDEN	14	1.2	.	5	.
HOSMER	10	.99	.	.	.
JULESBURG	3	.36	.	.	.
LORING	25	1.3	.	9	1.0
MACKSBURG	30	2.5	.	11	0.5
MARSHALL	26	2	.	10	.
MAURY	14	1.6	.	.	.
MODJESKA	9	.94	.	16	2.0
MUSCATINE	35	2.7	.	9	.
MUSCATINE	26	2.4	.	8	.
NORGE	18	1.5	.	.	.
PALOUSE	30	.	.	.	.
PAYNE	14	.	.	.	.
PROMISE	23	2.4	.	10	1.0
PULLMAN	8	.	.	.	.
PULLMAN	8	.	TR	.	.
RICHFIELD	9	.90	.	4	.
RUSSIAN	17	1.4	.	.	.
SHELBY	16	1.4	TR	.	.
TAMA	18	1.7	.	12	.
ULY	13	1.2	.	.	.
WYMORE	25	.	.	.	.
ZANESVILLE	11	1.1	.	.	.

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Table 9. Chemical characterization data for the highly weathered soils as determined by SCS.

Soil Series	Organic C	Total N	Calcium Carbonate	Fe	Al
	g kg^{-1}				
AGAWAM	18	.	.	8	3.0
AGAWAM	27	.	.	12	.
APPLING	18	0.6	.	.	.
BERTIE	4	.	.	.	.
CARIBOU	19	.	.	16	.
CATALINA	38	3.2	.	.	.
DAVIDSON	11	0.8	.	17	2.0
DOTHAN	7	.	.	5	1.0
HOLLAND	33	1.5	.	13	.
LAKE	6	0.3	.	.	.
LAKELAND	7	0.4	.	.	.
MADISON	14	0.8	.	.	.
MARDIN	17	.	.	14	.
MILLHOPPER	6	0.3	.	.	.
NORFOLK	6	0.5	.	2	.
PAXTON	31	.	.	10	.
RABUN	25	2.1	.	.	.
RUSTON	5	.	.	2	0.5
SASSAFRAS-LIKE	30	2.2	.	5	2.0
SOSA	10	.92	.	18	1.0
STOCKBRIDGE	.	.	.	.	.
TIFTON	5	0.3	.	5	1.0

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Table 10. Soil test P of the calcareous soils as measured by several methods by the Texas Agricultural Extension Service.

Soil Series	Resin	Bray I	Mehlich I	Olsen	Texas A&M	Water	P Avail. Index
	---------- mgP kg soil^{-1} ----------						
AVONDALE	14	8	49	9	452	.46	.600
BONE	25	34	92	13	29	.68	.722
BOSQUE	13	8	4	16	97	.41	.523
CATALPA	22	51	81	34	54	.34	.525
COLY	10	5	152	8	58	.28	.497
CROFTON	7	3	28	7	70	.14	.505
FRUITLAND	13	23	127	6	93	.31	.282
HOCHHEIM	18	11	40	8	22	.14	.460
HOUSTON BLACK	8	2	4	8	58	.08	.527
JOPLIN	16	18	53	11	20	.26	.570
KENT	11	10	50	9	22	.09	.522
KIDMAN	56	77	338	38	101	1.1	.553
LEEPER	41	51	87	30	84	.18	.541
MILLVILLE	13	26	18	12	113	.28	.222
SANPETE	12	1	3	10	152	.09	.188
VENUS	6	12	10	3	35	.17	.540
WAYDEN	15	11	4	8	27	.14	.607
WITT	32	47	143	18	43	.59	.635

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Table 11. Soil test P of the slightly weathered soils as measured by several methods by the Texas Agricultural Extension Service.

Soil Series	Resin	Bray I	Mehlich I	Olsen	Texas A&M	Water	P Avail. Index
	---------- mgP kg soil^{-1} ----------						
ABSTED	15	27	100	15	17	.72	.663
ACUFF	41	79	113	42	85	2.1	.718
ALO	12	13	23	13	11	.19	.423
AMARILLO	4	8	12	4	26	.16	.623
AMSTERDAM	21	27	206	15	38	.42	.735
BEARPAW-LIKE	17	24	66	11	19	.38	.490
BEARPAW-LIKE	16	33	65	16	16	.32	.627
CALLOWAY	5	6	3	5	6	.07	.071
CHILCOTT	53	79	215	42	45	1.2	.691
CRETE	29	46	43	21	29	.62	.520
FAYETTE	14	27	22	19	19	.25	.383
GRUNDY	20	27	36	19	32	.19	.423
HAGERSTOWN	6	11	6	4	5	.06	.128
HARNEY	21	12	76	9	13	.22	.633
HASTINGS	17	16	39	16	12	.22	.465
HAYDEN	13	16	22	12	18	.28	.528
HOSMER	11	13	9	12	11	.15	.323
JULESBURG	9	15	30	7	11	.34	.638
LORING	5	7	6	4	7	.13	.163
MACKSBURG	32	39	30	23	22	.22	.538
MARSHALL	29	38	35	19	24	.19	.455
MAURY	11	39	49	19	29	.09	.215
MODJESKA	16	25	40	11	23	.29	.238
MUSCATINE	30	23	20	15	17	.46	.442
MUSCATINE	14	15	11	12	12	.19	.333
NORGE	5	4	7	3	5	.14	.450
PALOUSE	25	32	87	15	18	.31	.212
PAYNE	18	20	23	11	18	.33	.653
PROMISE	29	19	107	15	28	.52	.633
PULLMAN	27	32	61	11	23	.30	.703
PULLMAN	8	11	24	5	15	.11	.660
RICHFIELD	19	21	71	9	11	.38	.673
RUSSIAN	10	12	90	9	14	.10	.258
SHELBY	10	5	13	5	5	.10	.588
TAMA	16	12	10	8	7	.09	.490
ULY	10	5	62	4	5	.10	.603
WYMORE	22	28	22	14	12	.13	.493
ZANESVILLE	15	29	25	16	22	.15	.250

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Table 12. Soil test P of the highly weathered soils as measured by several methods by the Texas Agricultural Extension Service.

Soil Series	Resin	Bray I	Mehlich I	Olsen	Texas A&M	Water	P Avail. Index
	---------- mgP kg soil^{-1} ----------						
AGAWAM	43	206	147	30	48	.46	.463
AGAWAM	16	107	45	24	23	.10	.208
APPLING	4	9	5	4	5	.07	.177
BERTIE	11	80	68	22	27	.83	.468
CARIBOU	21	136	71	45	19	.09	.177
CATALINA	3	3	2	4	4	.07	.057
DAVIDSON	6	21	17	12	14	.07	.118
DOTHAN	9	47	44	14	21	.84	.328
HOLLAND	11	110	53	30	14	.14	.072
LAKE	16	105	71	33	24	.64	.443
LAKELAND	27	222	106	44	26	.56	.298
MADISON	7	9	6	12	4	.07	.212
MARDIN	16	56	30	24	16	.25	.302
MILLHOPPER	18	85	58	24	21	.97	.447
NORFOLK	28	107	84	50	24	1.9	.513
PAXTON	5	33	8	8	5	.06	.088
RABUN	5	7	4	7	4	.10	.098
RUSTON	4	4	4	2	2	.09	.285
SASSAFRAS-LIKE	15	47	31	20	26	.45	.310
SOSA	4	6	6	3	5	.09	.290
STOCKBRIDGE	4	4	16	6	3	.07	.145
TIFTON	9	47	42	10	19	.22	.378

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Table 13. Inorganic and organic P fractionation of the calcareous soils as determined by the Saskatchewan Institute of Pedology.

Soil Series	Inorganic					Organic				
	Resin	Bicrb	Hydrox	Soni	Acid	Bicrb	Hydrox	Soni	Res	Total
	mg P kg soil^{-1}									
AVONDALE	25	14	8	1	820	4	11	1	161	965
BONE	29	8	42	14	107	4	27	8	157	385
BOSQUE	32	18	16	2	240	5	29	3	175	505
CATALPA	59	29	71	9	70	10	72	7	341	667
COLY	13	5	7	2	372	4	34	9	165	604
CROFTON	5	4	6	2	536	4	18	3	187	754
FRUITLAND	.	.	.	.	.	.	.	.	.	.
HOCHHEIM	16	11	37	7	189	10	47	5	224	554
HOUSTON BLACK	10	9	22	2	342	7	57	6	281	724
JOPLIN	19	10	29	5	146	5	34	7	191	434
KENT	10	7	16	4	128	8	34	6	92	309
KIDMAN	82	23	43	6	501	4	28	4	179	833
LEEPER	65	38	110	17	137	10	43	3	391	805
MILLVILLE	18	12	21	3	484	4	39	5	187	759
SANPETE	21	19	8	1	293	5	21	4	120	475
VENUS	5	3	4	0	46	4	8	2	68	135
WAYDEN	15	9	16	2	264	6	39	4	266	594
WITT	47	12	30	4	203	6	32	6	107	424

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Table 14. Inorganic and organic P fractionation of the slightly weathered soils as determined by the Saskatchewan Institute of Pedology.

Soil Series	Inorganic					Organic				
	Resin	Bicrb	Hydrox	Soni	Acid	Bicrb	Hydrox	Soni	Res	Total
	mg P kg soil^{-1}									
ABSTED	17	10	35	7	183	8	27	5	132	409
ACUFF	95	22	30	6	51	8	43	7	161	418
ALO	17	7	14	5	65	6	31	8	136	253
AMARILLO	9	2	3	1	12	2	9	1	58	90
AMSTERDAM	30	9	19	4	467	4	31	5	203	735
BEARPAW-LIKE	20	9	29	7	197	13	50	9	200	515
BEARPAW-LIKE	31	17	44	10	140	17	57	7	256	592
CALLOWAY	4	4	19	5	9	17	58	10	101	216
CHILCOTT	63	36	96	17	448	14	56	7	171	874
CRETE	38	22	46	8	75	35	90	11	211	524
FAYETTE	20	17	65	14	75	43	79	14	182	507
GRUNDY	28	21	49	8	98	38	87	6	222	551
HAGERSTOWN	7	11	139	34	66	27	185	31	294	774
HARNEY	17	7	11	2	209	14	67	9	238	562
HASTINGS	18	8	15	4	130	31	78	11	193	487
HAYDEN	14	11	36	8	60	14	46	12	114	315
HOSMER	9	8	56	13	47	21	95	16	174	438
JULESBURG	12	4	9	2	80	5	25	5	53	183
LORING	11	5	16	4	6	8	36	13	97	192
MACKSBURG	39	24	69	10	87	68	141	9	260	714
MARSHALL	33	20	50	9	72	44	140	12	286	665
MAURY	37	39	283	85	309	23	135	26	611	1505
MODJESKA	26	21	69	19	70	11	37	6	271	511
MUSCATINE	27	14	41	9	48	68	156	17	262	635
MUSCATINE	18	11	41	7	62	119	188	26	171	650
NORGE	9	3	6	2	23	12	55	12	158	273
PALOUSE	27	15	30	4	284	14	54	3	205	616
PAYNE	16	7	14	3	27	7	34	3	153	244
PROMISE	30	13	31	7	199	12	77	12	330	682
PULLMAN	29	9	18	3	106	5	26	6	183	358
PULLMAN	11	4	8	1	55	2	17	2	151	262
RICHFIELD	17	8	18	4	146	12	40	6	127	387
RUSSIAN	11	15	53	12	259	13	36	9	179	572
SHELBY	7	4	12	3	63	16	72	6	199	371
TAMA	16	9	29	5	31	24	92	6	286	490
ULY	5	3	5	1	200	9	56	5	191	502
WYMORE	24	14	42	8	58	37	100	15	220	555
ZANESVILLE	26	22	94	21	29	17	52	18	233	502

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Table 15. Inorganic and organic P fractionation of the highly weathered soils as determined by the Saskatchewan Institute of Pedology.

Soil Series	Inorganic					Organic				
	Resin	Bicrb	Hydrox	Soni	Acid	Bicrb	Hydrox	Soni	Res	Total
	mg P kg soil^{-1}									
AGAWAM	61	81	632	59	290	26	3	32	141	1429
AGAWAM	29	64	691	64	128	36	14	37	162	1283
APPLING	2	4	22	4	1	9	23	5	54	121
BERTIE	25	34	78	7	25	12	31	7	40	255
CARIBOU	31	110	502	41	103	28	116	24	172	1099
CATALINA	5	4	83	17	3	27	108	17	377	591
DAVIDSON	.	.	.	.	.	.	.	.	.	.
DOTHAN	20	18	64	8	29	4	30	9	89	262
HOLLAND	32	92	649	76	102	15	83	19	201	1211
LAKE	.	.	.	.	.	.	.	.	.	.
LAKELAND	38	85	256	17	51	10	44	5	34	532
MADISON	6	6	37	8	4	11	55	14	89	243
MARDIN	.	.	.	.	.	.	.	.	.	.
MILLHOPPER	24	37	156	25	27	16	6	5	50	357
NORFOLK	30	58	113	11	25	15	33	4	51	343
PAXTON	8	18	226	33	36	43	222	51	183	811
RABUN	11	11	137	33	8	31	116	38	946	1317
RUSTON	2	1	6	2	3	6	16	3	42	78
SASSAFRAS-LIKE	27	25	75	13	17	38	122	29	89	427
SOSA	4	3	24	7	7	10	66	14	165	305
STOCKBRIDGE	7	6	42	10	70	23	188	49	198	565
TIFTON	37	17	62	10	14	8	45	10	54	245

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Table 16. Relationships between labile P (Pil) and Bray I, Mehlich I, Olsen, and Texas A&M P (mg P kg soil^{-1}) (modified from Sharpley et al., 1984a).

Equation	Number of Observations	Root Mean Square Error	R^2
Calcareous			
Pil = 0.549 BP + 6.3	18	5.4	0.83
1.095 OP + 3.4		7.1	0.72
0.104 MP + 10.6		9.5	0.50
-0.004 TP + 18.8		13.3	0.00
Slightly weathered			
Pil = 0.532 BP + 4.9	36	5.5	0.75
1.042 OP + 3.5		5.6	0.74
0.134 MP + 10.9		8.5	0.39
0.508 TP + 7.60		7.8	0.49
Highly weathered			
Pil = 0.140 BP + 3.6	21	4.7	0.79
0.552 OP + 2.1		6.3	0.63
0.243 MP + 2.8		3.7	0.87
0.774 TP + 0.3		5.1	0.76

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Table 17. Equations for estimation of fertilizer P availability index (F1) from $CaCO_3$ (g kg^{-1}), labile P (Pil, mgP kg $soil^{-1}$), base saturation (BS, %), pH (PH), clay (CL, %), and organic carbon (OC, g kg^{-1}) (modified from Sharpley et al., 1984b).

Equation	Number of Observations	Root Mean Square Error	R^2
Calcareous			
$F1 = -0.00055\ CaCO_3 + 0.56$	18	0.103	0.48
Slightly Weathered			
$F1 = 0.0038\ BS + 0.0038\ Pil + 0.12\ PH - 0.71$	36	0.104	0.72
Highly Weathered			
$F1 = -0.043\ Ln\ CL + 0.0044\ Pil - 0.0057\ OC + 0.39$	21	0.073	0.78

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Table 18. Relationships between Bray I (BP), Mehlich I (MP), Olsen (OP), and Texas A&M (TP) (mg P kg soil^{-1}) soil-P test methods (modified from Sharpley et al., 1984a).

Equation	Number of Observations	Root Mean Square Error	R^2
Calcareous			
BP = 1.891 OP - 3.94	18	10.5	0.78
BP = 0.173 MP + 8.93		15.6	0.50
BP =-0.025 TP + 24.28		22.0	0.014
OP = 0.061 MP + 9.16		8.7	0.28
OP = 0.002 TP + 13.96		10.3	0.00
MP = 0.014 TP + 77.23		90.8	0.00
Slightly Weathered			
BP = 1.866 OP - 1.50	36	5.6	0.90
BP = 0.212 MP + 13.28		14.0	0.37
BP = 0.998 TP + 4.21		9.5	0.71
OP = 0.103 MP + 8.43		7.3	0.34
OP = 0.500 TP + 3.73		5.0	0.69
MP = 1.986 TP + 10.59		41.2	0.34
Highly Weathered			
BP = 3.701 OP - 5.47	21	35.4	0.71
BP = 1.553 MP + 2.20		21.9	0.88
BP = 4.541 TP - 7.00		38.8	0.65
OP = 0.300 MP + 7.20		8.9	0.64
OP = 0.843 TP + 6.00		11.2	0.43
MP = 3.116 TP - 9.12		16.4	0.83

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